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On the interpretation of the age and chemical composition of composite stellar populations determined with line-strength indices

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ABSTRACT

We study the simple stellar population-equivalent (SSP-equivalent) age and chemical composition measured from the Lick/IDS line-strength indices of composite stellar populations (CSPs). We build two sets of ∼30 000 CSP models using stellar populations synthesis models, combining an old population and a young population with a range of ages and chemical compositions representative of early-type galaxies. We investigate how the SSP-equivalent stellar parameters of the CSPs depend on the stellar parameters of the two input populations; how they depend on *V*-band luminosity-weighted stellar parameters; and how SSP-equivalent parameters derived from using different Balmer-line indices can be used to reveal the presence of a young population on top of an old one. We find that the SSP-equivalent age depends primarily on the age of the young population and on the mass fraction of the two populations, and that the SSP-equivalent chemical composition depends mainly on the chemical composition of the old population. Furthermore, the SSP-equivalent chemical composition tracks quite closely the *V*-band luminosity-weighted one, while the SSP-equivalent age is strongly biased towards the age of the young population. In this bias, the age of the young population and the mass fraction between old and young population are degenerate. Finally, assuming typical error bars, we find that a discrepancy between the SSP-equivalent parameters determined with different Balmer-line indices can reveal the presence of a young stellar population on top of an old one as long as the age of the young population is less than ∼2.5 Gyr and the mass fraction of young-to-old population is between 1 and 10 per cent.

Key words: galaxies: stellar content.

1 INTRODUCTION

The knowledge of age and chemical composition of stars in early-type galaxies is a fundamental piece in the puzzle of galaxy formation and evolution. For a long time, optical-wavelength studies in this direction have been hampered by the age–metallicity degeneracy: an age variation of a factor of ∼3 mimics a metallicity variation of a factor of ∼2 in the spectra of old stellar populations (e.g. Faber 1973; O'Connell 1986; Worthey 1994, hereafter W94). The effort of various authors during the past two decades culminated in the work of W94, who showed that age and metallicity can be disentangled by the joint use of pairs of line-strength indices, one metal-line and one Balmer-line index, measured from the optical spectra of galaxies. A system of line-strength indices was defined (the Lick/IDS system; see Burstein et al. 1984; Worthey et al. 1994 and references therein; Worthey & Ottaviani 1997) and is now widely used in order to determine the age t, metallicity [Z/H] and abundance ratio [E/Fe] of stars in galaxies ([E/Fe] is defined in Trager et al. 2000a as a way of parametrizing deviations from the solar abundance pattern).

In practice, one compares the indices measured from the optical spectrum of a galaxy to their values predicted by stellar populations models (provided for example by W94; Vazdekis 1999; Bruzual & Charlot 2003, hereafter BC03; Thomas, Maraston & Bender 2003). The stellar t, [Z/H] and [E/Fe] of the galaxy are the ones of the model whose indices best agree with the measured ones. Because each model consists of a single-burst stellar population (SSP) whose stars, unlike in real galaxies, all have the same t, [Z/H] and [E/Fe], the derived stellar parameters are labelled as SSP-equivalent. We will refer to them as $t_{\rm SSP}$, $[{\rm Z/H}]_{\rm SSP}$ and $[{\rm E/Fe}]_{\rm SSP}$.

Early-type galaxies are the most massive stellar systems for which the SSP approximation seems to hold. Therefore, many authors have measured their line-strength indices in order to determine their stellar content (see e.g. Trager et al. 2000b; Caldwell, Rose & Concannon 2003; Denicolò et al. 2005; Thomas et al. 2005; Clemens et al. 2006). However, many results suggest that recent star formation occurred in these galaxies (Trager et al. 2000b; Yi et al. 2005), so that a small fraction of their current stellar mass formed a few gigayears

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ago. It is natural to wonder about the meaning of the line-strength indices analysis under such circumstances (i.e. in the presence of more than one SSP in the same galaxy). How do the SSP-equivalent parameters relate to the average properties of a galaxy and to the ones of the many SSPs that it hosts? And what do we actually learn from SSP-equivalent parameters?

Previous authors have already looked into this problem. Using a limited number of models of composite stellar populations (CSPs), Trager et al. (2000b) found that the SSP-equivalent age is heavily biased towards the age of the young stars present in a galaxy. In this paper, we address the same questions in a more systematic and extensive way from the point of view of the stellar population models.

We build two sets of CSPs by using the models of BC03 and W94. Each data set contains $\sim 3 \times 10^4$ CSP models composed of one old and one young SSP. Different CSPs correspond to different stellar parameters of the parent SSPs. The old SSP (SSP_1) is always chosen to be more massive than the young one (SSP_2), as inferred in many early-type galaxies (e.g. Leonardi & Worthey 2000; Trager et al. 2000b; Jeong et al. 2006). We analyse the line-strength indices of the CSPs and derive the corresponding t_{SSP}, $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ as is usually done for observed galaxies. We then analyse how the result depends on the input parameters (t_1, $[Z/H]_1$, $[E/Fe]_1$, t_2, $[Z/H]_2$, $[E/Fe]_2$ and $\mu = M_2/M_1$, where M is the stellar mass) and on the luminosity-weighted properties of the CSPs. We restrict our study to systems composed of only two SSPs because this case is still relatively easy to treat and might be a reasonable first-order approximation for early-type galaxies. In Section 2, we explain in some details the construction of the two data sets; we present the results in Section 3, and finally draw some conclusions.

2 MODELS OF CSPs

We define a set of old and young SSPs in Table 1. All the possible combinations of one old and one young SSP for each of the values of the mass fraction μ give the 30 720 CSP models that form each of the data sets. A data set consists of a seven-dimensional grid in the parameters (t_1, $[Z/H]_1$, $[E/Fe]_1$, t_2, $[Z/H]_2$, $[E/Fe]_2$, μ). At each position in the grid, we store a vector that contains the line-strength indices of the two input SSPs and of the resulting CSP, the luminosity-weighted stellar parameters (t_{LW}, $[Z/H]_{LW}$, $[E/Fe]_{LW}$) and the SSP-equivalent stellar parameters (t_{SSP}, $[Z/H]_{SSP}$, $[E/Fe]_{SSP}$).

The luminosity-weighted stellar parameters are defined in terms of the V-luminosity of the parent populations at the respective ages (i.e. taking into account the change in mass-to-light ratio as a population ages).

Table 1. Input parameters for the CSPs.

Parameter	Values
t_1 (Gyr)	10.0, 13.0
$[Z/H]_1$	−0.15, 0.0, 0.15, 0.3
$[E/Fe]_1$	0.0, 0.15, 0.3, 0.45
t_2 (Gyr)	1,1.4,1.8,2.5,3.4, 4.7
$[Z/H]_2$	0.0, 0.15, 0.3, 0.45
$[E/Fe]_2$	−0.15, 0, 0.15, 0.3
$\mu = M_2/M_1$	0.0, 0.001, 0.005, 0.01, 0.025, 0.05, 0.1, 0.2, 0.35, 0.5

Notes. Stellar parameters are labelled as '1' and '2' corresponding to the old population (SSP_1) and the young population (SSP_2), respectively. The last row lists the values adopted for the mass fraction between the two populations.

The SSP-equivalent parameters are determined by comparing the Lick/IDS line-strength indices Mg*b*, Fe5270 and Fe5335 and a Balmer-line index of the CSP to their values according to models (BC03 or W94 depending on the data set). As Balmer-line index we use alternatively Hβ, Hγ_A, Hγ_F, Hδ_A or Hδ_F, obtaining SSP-equivalent parameters for each of them separately. These will then be labelled according to the Balmer-line index used in deriving them (e.g. $t_{H\beta}$ is the SSP-equivalent age derived using Mg*b*, Fe5270 and Fe5335 and Hβ). The use of different Balmer lines is important because they respond differently to the presence of a young stellar component on top of the old one (Schiavon, Caldwell & Rose 2004).

Although W94 and BC03 models are available only with [E/Fe] = 0, Table 1 contains also parent SSPs of non-solar [E/Fe]. In these cases, we correct the line-strength indices given by the models according to the [E/Fe] variations. We then use the corrected values when both building the CSP models and measuring their SSP-equivalent parameters. The correction scheme is the one described in Trager et al. (2000a) but improved by the use of new response functions computed and kindly provided by G. Worthey. For details, see Trager, Faber & Dressler (2006).

Fig. 1 shows the distribution of the solar-[E/Fe] parent SSPs drawn from the BC03 models and of the resulting CSPs on the plane [[MgFe], Hβ], where age and metallicity are efficiently decoupled. The points are plotted on top of the BC03 solar-[E/Fe] model grid. The CSP models cover most of the area where early-type galaxies have been observed to lie (e.g. Trager et al. 2000a; Denicolò et al. 2005; Thomas et al. 2005).

3 RESULTS

We calculate the covariance coefficients between the SSP-equivalent stellar parameters and the input parameters in order to understand which input parameters are mostly driving the variations in t_{SSP}, $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$. Table 2 shows the result of this calculation performed on the BC03 data set. The covariance coefficients do not change much when changing the Balmer-line index. In the table, we give the range within which each coefficient varies when changing Balmer-line index. Furthermore, we have verified that the W94 data set gives the same result. The following comments apply therefore to all Balmer-line indices and to both data sets.

(i) The variations in t_{SSP} are mostly driven by variations in t_2, the age of the young population, and μ, the mass fraction, while other parameters play a secondary role. The sign and absolute value of these two covariance coefficients clearly show the strong degeneracy between t_2 and μ: the same t_{SSP} can result from a small mass of young stars or a sufficiently large mass of older stars.

(ii) The variations in $[Z/H]_{SSP}$ are by far dominated by variations in $[Z/H]_1$, the metallicity of the old population. The mass fraction μ and the age of the young population t_2 also play a relevant role with the usual degeneracy. The latter correlations must be (at least partially) due to the fact that in the data set $[Z/H]_2$ is on average larger than $[Z/H]_1$. However, we have verified that the covariance coefficients between $[Z/H]_{SSP}$ and μ and between $[Z/H]_{SSP}$ and t_2 remain significantly larger than zero when considering a subset of models with $[Z/H]_1$ and $[Z/H]_2$ sampled in identical ways (in particular, the covariance coefficients drop by a factor of $\sim$2 and $\sim$1.3, respectively).

(iii) $[E/Fe]_{SSP}$ seems to be varying mostly because of variations in the abundance ratios of the two parent populations, with the old, massive population being dominant. As for $[Z/H]_{SSP}$, the correlation

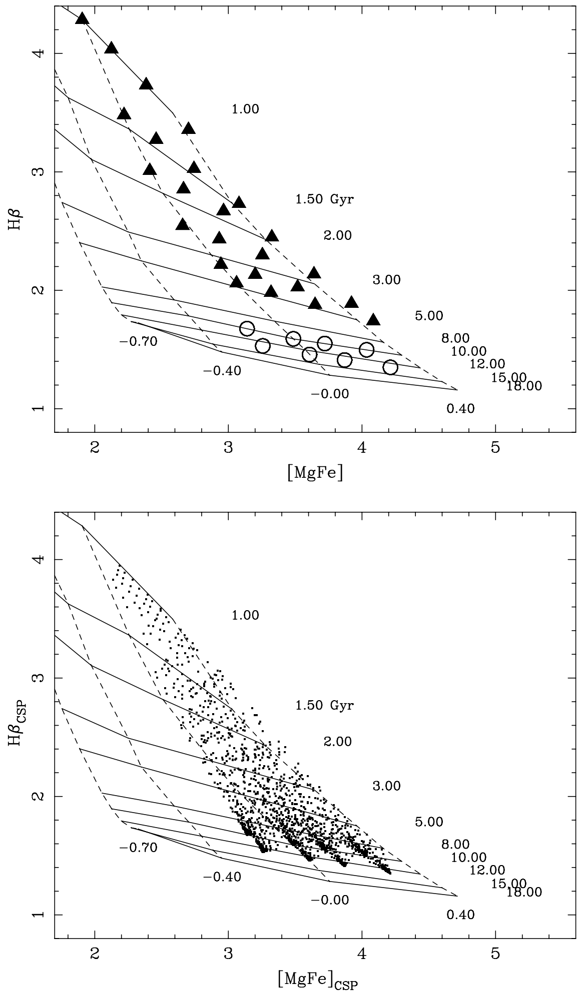

Figure 1. Top panel: BC03 parent SSPs of solar [E/Fe] plotted on top of the BC03 model grid; filled triangles represent the young SSPs (SSP_2); empty circles represent the old SSPs (SSP_1) which dominate the mass of the CSPs (see Table 1). Bottom panel: distribution of the BC03 CSPs built from the solar-[E/Fe] SSPs.

with μ and t_2 is only in part due to the different sampling of $[E/Fe]_1$ and $[E/Fe]_2$. Using a subset of models with identical sampling of $[E/Fe]_1$ and $[E/Fe]_2$ reduces the covariance coefficient with μ and increases the one with t_2 by a factor of $\sim$3.

Covariance coefficients highlight which of the input parameters play the dominant role in determining the variation of the SSP-equivalent ones. It is also interesting to see how the latter relates to the average properties of the model CSPs. Fig. 2 shows the comparison between the Hβ-based SSP-equivalent parameters and the V-band luminosity-weighted ones. The behaviour is substantially the same when using different Balmer-line indices.

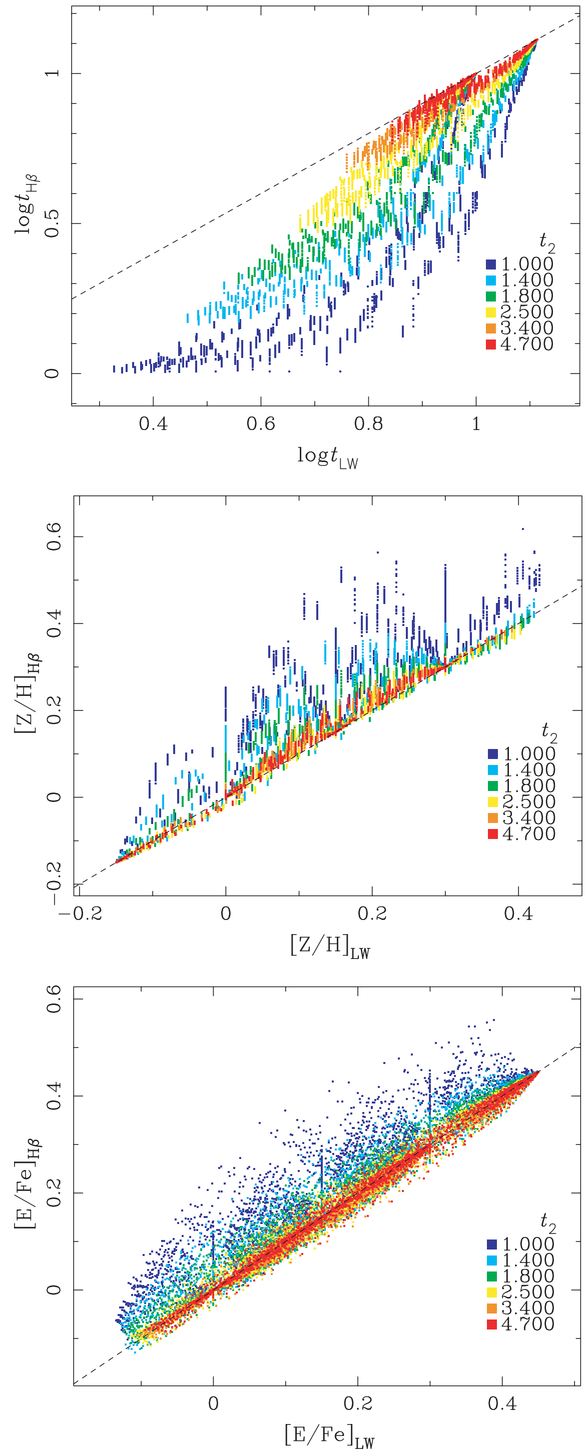

Figure 2. Hβ-based t_{SSP}, $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ plotted versus the respective V-band luminosity-weighted quantities using the BC03 data set. The dashed line of each plot is the identity line. The colour codes t_2.

Table 2. Covariance coefficients between SSP-equivalent parameters and input parameters.

	$\log t_1$	$\log t_2$	$[Z/H]_1$	$[Z/H]_2$	$[E/Fe]_1$	$[E/Fe]_2$	μ
$\log t_{SSP}$	0.05, 0.10	*0.51, 0.56*	−0.14, −0.07	0.09, 0.12	−0.01, 0.01	−0.01, 0.00	*−0.57, −0.65*
$[Z/H]_{SSP}$	0.02, 0.06	−0.19, −0.32	*0.78, 0.85*	0.09, 0.16	−0.01, 0.01	0.00, 0.01	0.25
$[E/Fe]_{SSP}$	0.00, 0.01	−0.11, −0.01	0.02, 0.07	−0.06, −0.04	*0.85, 0.87*	0.23	−0.19, −0.17

Notes. Each entry is the range within which the covariance coefficient varies when changing the Balmer-line index (or the value of the coefficient if this does not vary). The largest coefficients for each SSP-equivalent parameter are given in italics.

$[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ seem to track quite closely $[Z/H]_{LW}$ and $[E/Fe]_{LW}$, respectively; strong deviations are observed only for the youngest t_2. On the other hand, t_{SSP} is always much smaller than t_{LW} and lies somewhere between the latter and t_2. This effect was already known (Trager et al. 2000b). Its explanation is that the determination of t_{SSP} relies primarily on Balmer-line indices (see the model grid in Fig. 1). These are dominated by young stars and therefore t_{SSP} is strongly biased towards the age of the young stellar component. As Fig. 2 illustrates, the younger is the SSP_2 the stronger is this bias.

Fig. 2 demonstrates that it is not correct to use t_{SSP} as an estimate of when a galaxy formed its stars (yet, this is often done; see e.g. Clemens et al. 2006). A fair statement would be that t_{SSP} is a Balmer-line-weighted age and it should always be kept in mind that such an age is strongly biased towards the age of young stellar components. Furthermore, as highlighted by the covariance coefficient and confirmed by Fig. 2, the effect of t_2 and μ on t_{SSP} is degenerate. An increasingly older SSP_2 can produce the same t_{SSP} as long as μ is properly increased (in Fig. 2, μ increases towards decreasing t_{SSP} and t_{LW}).

As mentioned, SSP-equivalent parameters derived from different Balmer-line indices behave substantially in the same way (i.e. Fig. 2 looks roughly the same for all of them). However, different Balmer-line indices are sensitive to the presence of young stars at different levels (Schiavon et al. 2004). Because of this t_{SSP}, $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ (of a CSP) computed with different Balmer-line indices will not be in agreement. Fig. 3 illustrates this concept for a subset of the CSP models chosen to have solar chemical composition and $t_1 = 13$ Gyr. It can also be seen that the difference between Hβ- and Hγ_A-based SSP-equivalent parameters goes to zero for μ approaching 0 and 1 and peaks between these two extremes at a position dependent on t_2. Furthermore, Fig. 3 shows once more the degeneracy between t_2 and μ. The same difference between, e.g., $t_{H\beta}$ and $t_{H\gamma_A}$ can be caused by increasingly older SSP_2s as long as the mass fraction μ is sufficiently increased.

For clarity, Fig. 3 shows only a subset of the CSP models. A similar trend is anyway observed in the whole sample (and in W94 data set), showing that it is possible to detect the presence of a young stellar component on the basis of the disagreement between SSP-equivalent parameters obtained with different Balmer-line indices. We actually expect that more dramatic disagreements in, e.g., t_{SSP} are accompanied by larger differences in $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$. This is indeed observed and showed in Fig. 4, where the difference between Hβ- and Hγ_A-based $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ is plotted versus the difference in t_{SSP}. In particular the age–metallicity plot shows a very tight relation. This could be used in order to test the correctness of one's results.

Different Balmer lines can be used as a diagnostic for the presence of a young stellar component only as long as the differences in the SSP-equivalent parameters are larger than the observational errors. These are typically of 0.1 on the logarithm of t_{SSP} and on $[Z/H]_{SSP}$ and of 0.05 on $[E/Fe]_{SSP}$ (see e.g. Trager et al. 2000a; Thomas et al. 2005). Fig. 4 shows that with these errors t_{SSP} measurements are the most efficient in revealing a young component, allowing the detection of SSP_2s younger than ∼2.5 Gyr. As suggested by Fig. 3, this is, however, possible only within a certain range of μ. The actual range depends on t_2 but we find it to be roughly between 1 and 10 per cent. $[Z/H]_{SSP}$ and $[E/Fe]_{SSP}$ are only sensitive to SSP_2s younger than ∼1.5 Gyr with μ between 2 and 10 per cent. It is important to stress that for $\mu \geqslant 10$ per cent there is no detectable difference between the SSP-equivalent parameters derived from different Balmer-line indices. At these values of μ, the Balmer-line indices are so heavily dominated by the younger populations that they all 'see' the same age, which is very close to the age of the young population.

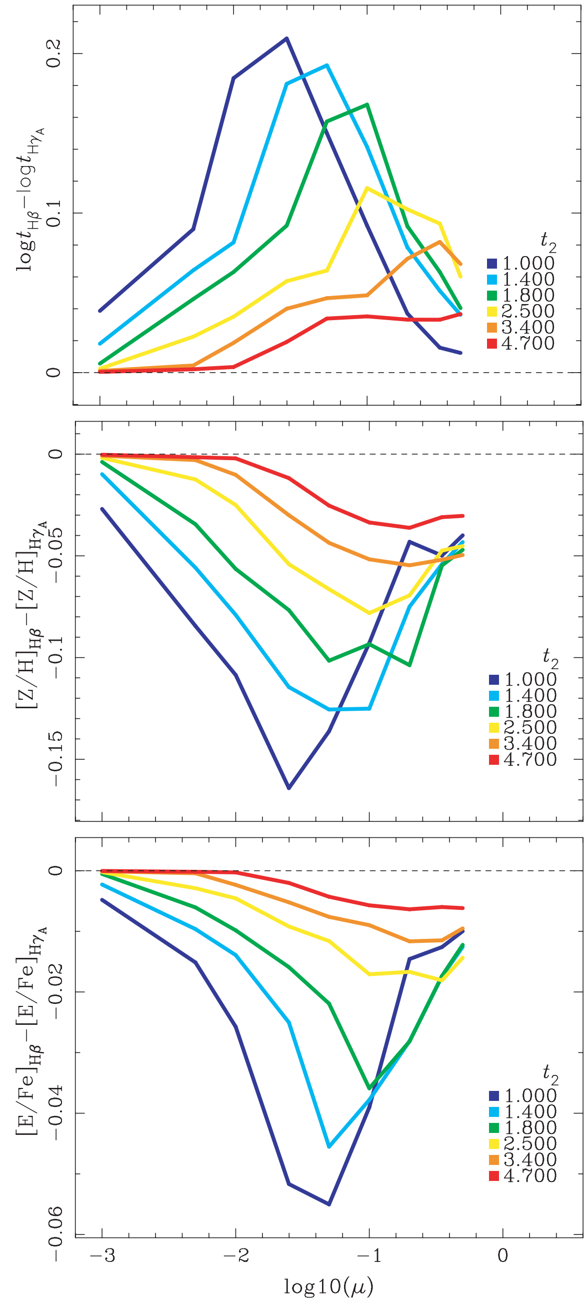

Figure 3. Difference between Hβ- and Hγ_A-based SSP-equivalent parameters as a function of μ. The plots are obtained using the BC03 data set and solar [Z/H] and [E/Fe] for both SSP_1 and SSP_2. The age of SSP_1 is fixed at 13 Gyr.

Figs 3 and 4 show another interesting feature: the largest difference between $t_{H\beta}$ and $t_{H\gamma_A}$ in Fig. 3 is small compared to the one in Fig. 4. Recall that Fig. 3 is relative to CSPs where both SSP_1 and SSP_2 have solar chemical composition, while Fig. 4 represents the whole BC03 sample, with [Z/H] growing significantly above solar. The two figures suggest that [Z/H] plays an important role with respect to the difference $t_{H\beta} - t_{H\gamma_A}$. Fig. 5 shows that indeed high (and therefore more easily detectable) differences in t_{SSP} occurr only at high metallicities. Similar plots hold for the difference in [Z/H] and

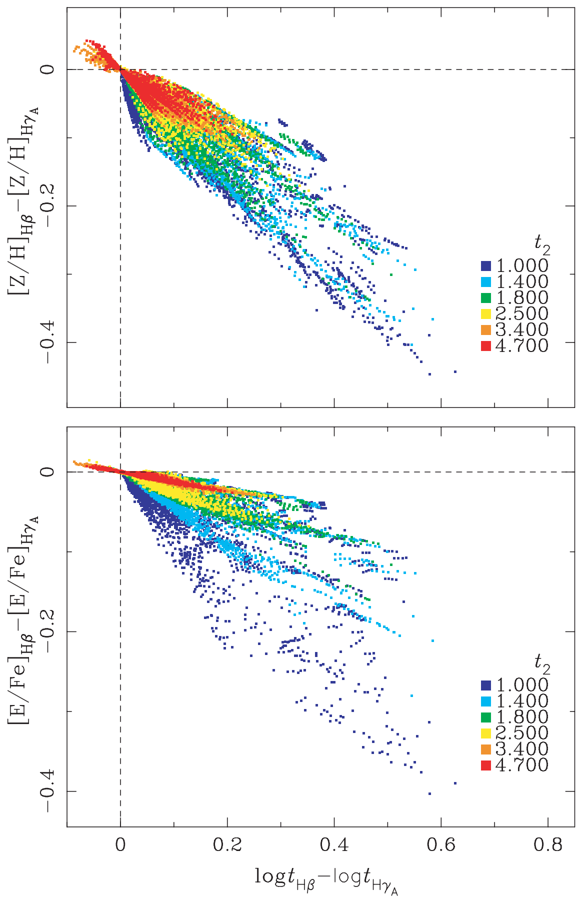

Figure 4. Difference between Hβ- and Hγ_A-based [Z/H]$_{\rm SSP}$ (top panel) and [E/Fe]$_{\rm SSP}$ (bottom panel) plotted versus the difference in $t_{\rm SSP}$. Each point corresponds to a BC03 CSP model. The presence of a young stellar population on top of an old one causes SSP-equivalent parameters based on different Balmer-line indices to disagree. This effect must be and indeed is observable simultaneously in $t_{\rm SSP}$, [Z/H]$_{\rm SSP}$ and [E/Fe]$_{\rm SSP}$. In particular, points seem to be distributed along a very tight relation in the age–metallicity plane.

[E/Fe]. We therefore find that the use of more than one Balmer-line index can reveal the presence of a young stellar population, but that this is possible only for a small range of t_2 and μ and depends also on the metallicity of the populations.

We would like to remind the reader that a disagreement between Balmer-line-based SSP-equivalent parameters, in principle revealing the presence of a young stellar component, could also result from the approach used when analysing the data. In particular, it is important to remember that different Balmer-line indices respond differently to variations in [E/Fe]. Thomas, Maraston & Korn (2004) and Thomas & Davies (2006) pointed out that this causes a discrepancy between SSP-equivalent parameters determined from different Balmer-line indices when using as a comparison models with solar [E/Fe] only. This effect could mimic the presence of a young stellar component. However, no such problem should occur when using models that account properly for [E/Fe] variations, as was done here.

Another delicate point when using Balmer-line indices is their increase caused by hot star populations like blue horizontal branch stars or blue stragglers (Maraston & Thomas 2000; Trager et al. 2005). Although this is not an issue for the present study, where

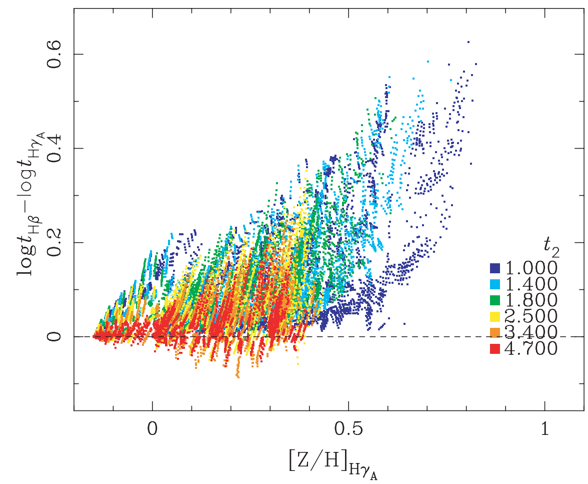

Figure 5. Difference between Hβ- and Hγ_A-based $t_{\rm SSP}$ plotted versus the Hγ_A-based [Z/H]. There is a clear trend that gives larger $t_{\rm SSP}$ discrepancies at larger [Z/H]$_{\rm SSP}$.

we do not explore the metal-poor regime at which these stars are expected to be found, this problem should always be kept into consideration when dealing with real data.

4 CONCLUSIONS

We have built two data sets of CSPs using BC03 and W94 models. Each CSP model in the data sets consists of an old SSP (SSP$_1$) and a younger, less massive one (SSP$_2$). We have investigated how the SSP-equivalent parameters determined by measuring the Lick/IDS line-strength indices of the CSPs depend on the stellar parameters of SSP$_1$ and SSP$_2$. By means of covariance coefficients, we have found that, regardless of the particular stellar populations, models used in building the CSPs and of the Balmer-line index used for the analysis: $t_{\rm SSP}$, the SSP-equivalent age, depends primarily on t_2, the age of the young population, and μ, the mass fraction between the two populations; variations in [Z/H]$_{\rm SSP}$, the SSP-equivalent metallicity, are mostly driven by variations in [Z/H]$_1$, the metallicity of the old population; and [E/Fe]$_{\rm SSP}$, the SSP-equivalent abundance ratio, depends mainly on [E/Fe]$_1$, the abundance ratio of the old population.

Furthermore, we have found that [Z/H]$_{\rm SSP}$ and [E/Fe]$_{\rm SSP}$ track quite closely the *V*-band luminosity-weighted metallicity and abundance ratio ([Z/H]$_{\rm LW}$ and [E/Fe]$_{\rm LW}$) except in the case of very young (and significantly massive) SSP$_2$. On the other hand, $t_{\rm SSP}$ does not follow $t_{\rm LW}$, being strongly biased towards the age t_2 of the young population. The SSP-equivalent age $t_{\rm SSP}$ is simply a Balmer-line-weighted age and should not be interpreted as the time passed since the formation of most of the stars in a galaxy.

Finally, as found by Schiavon et al. (2004), using more than one Balmer-line index can reveal the presence of a young stellar component on top of an old one. In this case, SSP-equivalent parameters derived from different Balmer-line indices give discrepant results. This is true, however, only for values of μ between 1 and 10 per cent and for $t_2 \leqslant 2.5$ Gyr assuming typical errors on $t_{\rm SSP}$, [Z/H]$_{\rm SSP}$ and [E/Fe]$_{\rm SSP}$. Furthermore, these discrepancies are higher at supersolar [Z/H]$_{\rm SSP}$. Finally, this method does not appear to break the degeneracy between the age and the mass fraction of the young population, especially when considering the size of the typical error bars. In this respect, what is really needed is an age-sensitive index dependent on the age of the old stellar population (i.e. red giant branch stars), to be used in combination with Balmer-line indices.

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